

# ***U.S. PATENT APPLICATION***

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***Invention:*** METHOD OF ION BEAM MILLING A GLASS SUBSTRATE PRIOR TO  
DEPOSITING A COATING SYSTEM THEREON, AND CORRESPONDING  
SYSTEM FOR CARRYING OUT THE SAME

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## ***SPECIFICATION***

This is a continuation-in-part (CIP) of each of U.S. Patent Application Serial Nos. 09/657,132, filed Sept. 7, 2000; 09/627,441, filed July 28, 2000; 09/617,815 filed July 17, 2000; 09/303,548, filed May 3, 1999; 09/442,805, filed Nov. 18, 1999; and 09/583,862  
5 filed June 1, 2000, the disclosures of which are all hereby incorporated herein by reference.

**METHOD OF ION BEAM MILLING A GLASS SUBSTRATE PRIOR TO  
DEPOSITING A COATING SYSTEM THEREON, AND CORRESPONDING  
SYSTEM FOR CARRYING OUT THE SAME**

This invention relates to a method and system for ion beam milling a glass  
10 substrate prior to depositing a coating system (e.g., diamond-like carbon (DLC) inclusive coating system) thereon.

**BACKGROUND OF THE INVENTION**

Each of the aforesaid parent applications relates to a DLC inclusive coating system  
15 on a substrate. Certain embodiments of certain of the parent applications relate to hydrophobic DLC inclusive coating systems where it is desirable to deposit a coating system having a high initial contact angle  $\theta$ .

Each of the coating systems disclosed in the aforesaid parent applications is  
excellent and works in an efficient manner. However, the coating systems may be  
20 improved by increasing their adherence to the underlying substrate. Moreover, it would

also be beneficial to increase the scratch resistance of such coating systems.

Thus, it will be appreciated by those skilled in the art that there exists a need(s) in the art for a method of manufacturing any of the coating systems in the aforesaid parent applications (or any other suitable coating system) in a manner so as to improve adherence to the underlying substrate and/or to make the resulting coated article more scratch resistant. It is a purpose of different embodiments of this invention to fulfill one or more of the above described needs in the art, and/or other needs which will become apparent to the skilled artisan once given the following disclosure.

### **SUMMARY OF THE INVENTION**

According to exemplary embodiments of this invention, a glass substrate is ion beam milled prior to deposition of a coating system (e.g., diamond-like carbon (DLC) inclusive coating system) thereon. Ion beam milling functions to remove or shave off a portion of the glass substrate in order to smoothen a surface of the substrate and/or remove/reduce nano-cracks which may have been present in the original substrate surface. Following the ion beam milling, the coating system is deposited on the smoothened surface of the substrate (e.g., via ion beam deposition, sputtering or the like).

According to certain exemplary embodiments of this invention, ion beam milling of a substrate prior to deposition of a coating system thereon enables resulting coating systems when deposited to better adhere to the substrate. Moreover, with respect to DLC

inclusive coating systems, it has surprisingly been found that such ion beam milling results in the coated article having improved scratch resistance. Ion beam milling may also function to reduce sodium (Na) content adjacent a milled surface of a soda inclusive glass substrate (e.g., soda-lime-silica glass substrate), thereby reducing the potential for sodium induced corrosion on the resulting coated article.

Coated articles made according to certain embodiments of this invention may be hydrophobic (e.g., shed water) or non-hydrophobic in different embodiments. In hydrophobic embodiments, an object of this invention is to provide a durable coated article that can shed or repel water (e.g. automotive windshield, automotive backlite, automotive side window, architectural window, bathroom shower glass, residential window, bathroom shower door, coated ceramic article/tile, etc.).

The hydrophobic nature of such articles is often characterized by relatively high initial contact angles  $\theta$ . For example, coated articles herein may be characterized by an initial contact angle  $\theta$  (i.e. prior to being exposed to environmental tests, rubbing tests, acid tests, UV tests, or the like) of at least about 55 degrees, more preferably of at least about 80 degrees, even more preferably of at least about 100 degrees and most preferably of at least about 110 degrees.

The instant ion beam milling invention may be used in conjunction with various types of DLC inclusive layer systems and other types of coating/layer systems, and is not intended to be limiting in that regard.

Generally speaking, certain exemplary embodiments of this invention seek to fulfill one or more of the above-listed needs in the art by providing a method of making a coated article comprising the steps of:

providing a substrate;

5        ion beam milling substantially an entire surface of the substrate so as to thin the substrate and smoothen the surface of the substrate; and

depositing a coating system on at least a portion of the ion beam milled surface of the substrate following said ion beam milling step so as to form the coated article.

In certain embodiments, the method of claim 27, wherein said ion beam milling step is performed in a manner so as to increase scratch resistance (SR) of the coated article by at least a factor of two, and/or so that an average surface roughness of the ion beam milled surface of the substrate following said ion beam milling is no more than about 80% of what an average surface roughness of the surface of the substrate was prior to said ion beam milling.

In certain embodiments, the depositing step comprises ion beam depositing at least one DLC inclusive layer on the ion beam milled surface of the substrate.

Certain exemplary embodiments of this invention further fulfill one or more of the above-listed needs by providing a coated article comprising:

an ion beam milled glass substrate; and

20        a coating system including at least one layer deposited on an ion beam milled surface of said glass substrate.

This invention will now be described with respect to certain embodiments thereof, along with reference to the accompanying illustrations.

### IN THE DRAWINGS

Figure 1 is a flowchart illustrating certain steps taken in accordance with an embodiment of this invention.

Figure 2 is a side cross sectional view of a portion of a glass substrate prior to ion beam milling.

Figure 3 is a side cross sectional view of the portion of the glass substrate of Fig. 2 after ion beam milling according to an embodiment of this invention has been performed (it is noted that the surface of the substrate to receive a coating system thereon has been smoothed by the milling, and certain nano-cracks have been removed).

Figure 4(a) is a schematic diagram from a side view perspective illustrating ion beam milling of a glass substrate according to an embodiment of this invention.

Figure 4(b) is a top view of the diagram of Fig. 4(a).

Figure 5(a) is a surface roughness versus number of ion beam passes graph illustrating that a greater number of ion beam milling passes smoothens a substrate surface more than a fewer number of such passes.

Figure 5(b) is a scratch resistance versus number of ion beam milling scans graph illustrating that scratch resistance of a tempered coated article improves as a function of ion beam milling scans over the underlying substrate prior to deposition of the coating system thereon.

5 Figure 5(c) is a scratch resistance versus number of ion beam milling scans graph illustrating that scratch resistance of an annealed coated article improves as a function of ion beam milling scans over the underlying substrate prior to deposition of the coating system thereon.

10 Figure 6(a) is a schematic side cross sectional view illustrating exemplary gases used in depositing a plurality of layers on a substrate after the ion beam milling of Figs. 1-5 has been performed in accordance with an exemplary embodiment of this invention.

Figure 6(b) is a side cross sectional view of a coated article resulting from the use of the gases of Fig. 6(a) during the article manufacturing process.

15 Figure 6(c) is a side cross sectional view of a coated article according to another embodiment of this invention, that is similar to the embodiment of Figs. 6(a)-(b) except that layers 4 and 6 are not included in this embodiment.

Figure 6(d) is a side cross sectional view of a coated article according to another embodiment of this invention, similar to the embodiments of Figs. 6(a)-(b) except that layers 2, 4 and 6 are not included in this embodiment.

Figure 6(e) is a side cross sectional view of a coated article according to yet another embodiment of this invention, similar to the embodiments of Figs. 6(a)-(b) except that layers 2 and 4 are not included in this embodiment.

Figure 7 is a side cross sectional view of a coated article according to another embodiment of this invention, wherein after the ion beam milling of the underlying substrate has been performed as in Figs. 1-5, DLC and FAS inclusive coating(s) or coating system of Figure 6(b) is/are provided over an intermediate layer(s).

Figure 8 is a side cross sectional view of a coated article according to another embodiment of this invention.

Figure 9(a) is a side cross sectional partially schematic view illustrating a low contact angle  $\theta$  of a water drop on a glass substrate.

Figure 9(b) is a side cross sectional partially schematic view illustrating the coated article of any of the Figs. 6-8 embodiments of this invention and the contact angle  $\theta$  of a water drop thereon (in embodiments where hydrophobicity is desired).

Figure 10 is a perspective view of a linear ion beam source which may be used in any embodiment of this invention for ion beam milling a glass substrate or for depositing DLC inclusive layer(s) and/or siloxane gas-deposited layer(s).

Figure 11 is a cross sectional view of the linear ion beam source of Figure 10.

Figure 12 is a diagram illustrating tilt angle as discussed herein in accordance with



certain embodiments of this invention.

Figure 13 is a flowchart illustrating certain steps taken according to exemplary embodiments where an optional FAS inclusive hydrophobic layer is thermally cured after being deposited on the ion beam milled substrate over at least one DLC inclusive layer.

5 Figure 14 illustrates a chemical structure of exemplary HMDSO.

Figure 15 illustrates a chemical structure of exemplary DMS.

Figure 16 illustrates a chemical structure of exemplary TMS.

Figure 17 illustrates a chemical structure of exemplary 3MS.

Figure 18 illustrates a chemical structure of exemplary OMCTSO.

10 Figure 19 illustrates a chemical structure of exemplary TMDSO.

Figure 20 illustrates a chemical structure of exemplary TEOS.

20 Figure 21 is a flowchart illustrating certain steps taken in accordance with an embodiment of this invention where the substrate is heated prior to or during ion beam deposition of a DLC inclusive layer(s) so as to make the resulting coating system more durable and/or more resistant to losing significant amounts of its original hydrophobic nature (such heating of the substrate may occur either before, during, and/or after the ion beam milling of Figs. 1-5).

**DETAILED DESCRIPTION OF  
CERTAIN EMBODIMENTS OF THIS INVENTION**

Referring now more particularly to the accompanying drawings in which like reference numerals indicate like elements throughout the accompanying views.

5        Figure 1 is a flowchart illustrating certain steps taken in accordance with an embodiment of this invention. First, in step 100, a glass substrate 1 is provided. The glass substrate may be from about 1-6 mm thick, more preferably from about 1.5 to 4.0 mm thick. Soda-lime-silica glass is preferred for the substrate, although other types of glass such as borosilicate glass may instead be used. The glass substrate 1 may be  
10        tempered or annealed in different embodiments of this invention.

15        Figure 2 is a side cross sectional view of a typical glass substrate 1 that is provided in step 100. As can be seen, a first major surface 105 of glass substrate 1 has a rather roughened surface, and also includes nano-cracks 106 defined therein. It has been found that the presence of the nano-cracks and surface roughness may adversely affect the  
20        adherence of a coating system to the surface 105 of the substrate 1.

     Referring back to Fig. 1, in step 101 the entire surface 105 of glass substrate 1 is then passed under one or more linear ion beam sources (preferably emitting focused ion beams, although non-focused beams may be used in certain embodiments) that extends across the entire surface 105 of the substrate in order to ion beam mill the surface 105 of  
20        substrate 1. This ion beam milling shaves off or removes a portion of the surface of the

glass substrate. For example, in certain embodiments of this invention, the ion beam milling of step 101 removes from about 2-100 angstroms ( $\text{\AA}$ ) (e.g., see depth "D" of shaved off glass in Fig. 2), more preferably from about 2-50  $\text{\AA}$ , even more preferably from about 4-20  $\text{\AA}$ , and most preferably from about 6-12  $\text{\AA}$  of glass from the surface of substrate 1.

Preferably, argon (Ar) ions are used to conduct the milling of substrate 1 (i.e., Ar gas is used in the ion beam source to produce mostly  $\text{Ar}^+$  ions that are directed toward the substrate surface to perform the milling) in step 101. Alternatively or additionally, other types of ions may instead be used (e.g., other inert gas ions such as Kr, Ne, and/or Xe) in the focused ion beam to perform the milling of substrate 1. Inert gas ions are preferred so as to minimize potential reactions with the substrate 1. The ion beam milling is preferably performed in a vacuum chamber where the ion beam source(s) and the substrate 1 being milled are located. A pressure of from about  $5.0 \times 10^{-4}$  to  $1.0 \times 10^{-4}$  is preferably maintained in this vacuum chamber where the substrate is located during the milling process. Additionally, each ion beam source is preferably operated during the ion beam milling process so that the beam has an ion energy of from about 300 to 5,000 eV, more preferably from about 1,500 to 2,000 eV, and most preferably from about 1,400 to 1,600 eV. One or more ion beam sources may be used during the milling process as will more fully described below.

Fig. 3 is a side cross sectional view of substrate 1 after step 101 (i.e., after the substrate 1 has been ion beam milled in step 101). As can be seen from comparing Fig. 2 (substrate 1 before milling) with Fig. 3 (substrate 1 after milling), the ion beam milling removes an amount "D" of glass from the surface of the substrate 1 and thereby

5 smoothens the surface of the substrate 1 so that a smoother surface 107 results.

Moreover, it can be seen that the ion beam milling removes of substantially reduces many of the nano-cracks 106 that were originally present at the surface of the substrate.

Referring back to Fig. 1, after the substrate 1 has been ion beam milled in such a manner, a coating system is deposited on smoothed surface 107 of the substrate in step 102. For example, as will be explained below with regard to Figs. 6-20, a DLC inclusive layer/coating system 5 be deposited on surface 107 in step 102. Additionally or alternatively, any other type of suitable coating system or layer (e.g., low-E coating system, or the like) may instead be deposited on surface 107 in step 102 via ion beam deposition, sputter, or any other suitable deposition process.

15 Surprisingly, it has been found that the ion beam milling of the substrate 1 as described above prior to deposition of a DLC inclusive layer or coating system (e.g., see coating system 5 in any of Figs. 6-8) on the smoothed surface 107 of the substrate results in a more scratch resistant DLC inclusive layer or coating system than if such ion beam milling had not occurred. Moreover, it has been found that the ion beam milling  
20 also results in improved adherence of the layer or coating system to surface 107 of

substrate 1.

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Figs. 4(a) and 4(b) illustrate an ion beam milling apparatus provided in a vacuum chamber 110 according to an embodiment of this invention consistent with Figs. 1-3. Fig. 4(a) is a side perspective view of the apparatus, while Fig. 4(b) is a top view of the apparatus. The ion beam milling apparatus includes conveyor 111 driven by at least one drive roll or gear 112 in order to move glass substrate(s) 1 through the apparatus in direction "F". Glass substrate 1 is on conveyor 111, and is moved through the apparatus in direction "F" so that the entire major surface 105 (including nano-cracks and surface roughness) of the substrate is passed under a plurality of ion beam sources 113-115. The preferably focused ion beams 34 (alternatively, beams 34 may be non-focused in certain embodiments) from ion beam sources 113, 114 and 115 impinge upon surface 105 of substrate (e.g., using Ar<sup>+</sup> ions) thereby milling the same as discussed above. As discussed above, the ion beams function to shave off a portion of the glass substrate 1 at the surface thereof so that the result is a smoother substrate surface 107 having fewer nano-cracks therein (see Fig. 3), on which a coating system 5 is to be deposited.

Ion beams 34 in Fig. 4(a) are shown hitting the surface 105 of substrate 1 at an angle  $\Omega$  of approximately 90 degrees. However, in other embodiments, ion beams 34 may be directed at surface 105 so as to impinge upon the same at angles of from about 30-90 degrees (e.g., from about 40-60 degrees) so as to achieve more of a shaving effect (i.e., so that glass is more easily removed from the substrate by the ion beams).

FIG. 4(a) and 4(b) illustrate the use of three separate fixed ion beam sources 113, 114, and 115, respectively, under which the substrate passes. The use of three fixed sources 113-115 under which the substrate 1 passes results in three ion beam milling "scans" of the substrate during the milling process. However, more or less than three ion beam sources may be used. For example, only 1 or 2 ion beam scans may be performed on the substrate 1 in certain embodiments, while 4-10 ion beam scans may be performed on the substrate 1 in other embodiments. Also, in the apparatus of Fig. 4 the linear ion beam sources 113-115 are fixed in place so that a scan results when the entire surface of the substrate 1 passes under the focused elongated beam 34 from the source. However, in alternative embodiments of this invention, a single linear ion beam source may instead be used that is capable of moving back and forth across a fixed substrate 1 (i.e., the number of ion beam "scans" of the substrate during the milling process is determined by the number of times the source moves back and/or forth across the substrate surface). For example, with a moving ion beam source and corresponding milling ion beam 34, if the source moves back and forth two times (two complete cycles of back and forth) across the entire surface of the substrate, then four ion beam scans have been carried out on the substrate 1.

Figure 5(a) illustrates that a substrate 1 becomes smoother the more ion beam milling scans that are performed on tempered soda-lime-silica glass substrates. "Rms" stands for root mean square airside surface roughness of the substrate 1 surface 105,



Chart A (before ion beam milling)

<u>Substrate Sample</u>	<u>Roughness (RMS)(nm)</u>	<u>Roughness(Avg)(nm)</u>
#1	2.58	2.12
#2	1.48	1.19

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Chart B (after ion beam milling)

<u>Substrate Sample</u>	<u>Scans</u>	<u>Roughness (RMS)(nm)</u>	<u>Roughness(Avg)(nm)</u>
#1	3	1.24	0.94
#1	12	0.99	0.72
#2	3	0.90	0.71
#2	12	0.93	0.67

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As can be seen in Charts A and B, the ion beam milling results in a significant smoothening of the substrate 1. After three ion beam scans, for example, sample #1's RMS surface roughness was reduced from 2.58 to 1.24 (i.e., the RMS surface roughness value after the ion beam milling was approximately 48% (1.24 divided by 2.58) of what it was prior to the milling). After twelve ion beam scans, sample #1's RMS surface roughness was reduced from 2.58 to 0.99 (i.e., the RMS surface roughness value after the ion beam milling was approximately 38% of what it was prior to the milling).



Figures 5(b) and 5(c) illustrate experimental results for different numbers of ion beam milling scans across two different respective annealed soda-lime-silica glass substrates with DLC inclusive coatings thereon, using 100 sccm Ar at 3,000 V. The coated articles tested in Figs. 5(b) and 5(c) were coated, as shown in Fig. 6(d), with a hydrogenated DLC inclusive layer (ta-C:H) using acetylene gas in the ion beam source used to deposit the DLC inclusive layer. Scratch resistance (SR) in Figs. 5(b) and (c) is defined herein as a function of how much pressure is needed to be applied to a ruby head (cylindrically shaped, 2.5 mm diameter, 3 mm height) mounted on the head of a linear taber abraser system, in order to cause a scratch to be formed in the surface of the coated article when the ruby head is moved across said surface. The ruby crystal has a hardness of 9 on the MOHs scale. The coated article (e.g., see Fig. 6(d)) is secured underneath the head and is linearly abraded at a given load. In the case of no scratch, the load is increased and the head is placed at an adjacent area of the article surface. This process is continued until a scratch becomes visible. A scratch herein is defined as being a visible mark seen at any azimuthal angle against a black surface. A light scratch is defined as being visible only at a normal angle to the article surface. Physically, a scratch implies the underlying glass is scratched with the thin DLC inclusive film/layer being punctured while with a light scratch the layer is either partially removed or deformed. It is noted that normal glass is scratched with the thin DLC inclusive coating thereon) scratches given a load of about 50-100 grams on the ruby head.

Fig. 5(b) relates to a single coated soda-lime-silica glass sheet, made for use in a laminated windshield, while Fig. 5(c) relates to a single coated soda-lime-silica annealed glass sheet. As can be seen in both Fig. 5(b) and Fig. 5(c), the scratch resistance (SR) goes up along with the number of ion beam milling scans. For example, for both coated articles in Figs. 5(b)-(c), when zero ion beam scans are performed (i.e., absent this invention), approximately 750 grams of pressure needs to be applied to the ruby head in order to cause scratches to be formed in the respective coated articles 1. However, after one ion beam scan across the entire surface 105 of the substrate prior to deposition of the coating thereon, approximately 925 grams of pressure were needed on the ruby head to form a scratch in the coated article of Fig. 5(b) and approximately 1100 grams of pressure were needed on the ruby head to form a scratch in the coated article of Fig. 5(c).

Surprisingly, Fig. 5 illustrates significant SR improvement after 3 ion beam milling scans of the substrate prior to deposition of the DLC inclusive layer. For example, in Figs. 5(b) and (c) approximately 6,100 grams of pressure were needed on the ruby head to form a scratch in the coated articles when four scans were used. This, of course, is a significant improvement over the 750 grams needed to form a scratch absent this invention. Thus, in preferred embodiments of this invention, ion beam milling as shown in Figs. 1-4 is performed in a manner so as to increase scratch resistance (as defined regarding Figs. 5(b) and 5(c)) of the resulting coated article by at least a factor of 2, more preferably by at least a factor of 3 as shown in Figs. 5(b) and 5(c).



#1	12	6.6	57	0.1	2.3	7	0.3	16.2	6.6	1.2
#2	3	9.7	60	0.2	1.0	3.2	1.3	17.5	3.7	0.7
#2	12	5.3	57	0.1	2.7	6.5	--	17.5	6.6	1.3

As can be seen in Charts C and D above, the ion beam milling reduces the amounts of Na and sulfur (S) at the surface of the substrate, and tends to increase the amount of iron (Fe) and/or argon (Ar) at the surface of the substrate. After three ion beam scans, for example, sample #1's sodium (Na) content was reduced from 13.5 to 11 (i.e., the Na atomic percentage content in the 75 angstroms adjacent the surface of the substrate after the ion beam milling was approximately 81% of what it was prior to the milling. After twelve ion beam scans, sample #1's Na content in the 75 angstroms adjacent the surface of the substrate was reduced from 13.5 to 6.6 (i.e., the Na atomic percentage content in the 75 angstroms adjacent the surface of the substrate after ion beam milling was approximately 49% of what it was prior to the milling). Thus, in certain embodiments of this invention, the Na content in the 20 or 75 angstroms of the substrate adjacent surface 107 after ion beam milling is preferably less than about 85% of what it was before the ion beam milling, more preferably less than about 75% of what it was before the ion beam milling. In a similar manner, in certain embodiments of this invention, the S content in the 20 or 75 angstroms of the substrate adjacent surface 107 after ion beam milling is preferably less than about 50% of what it was before the ion beam milling, more preferably less than about 40% of what it was before the ion beam milling.

After substrate 1 has been ion beam milled as discussed above regarding Figs. 1-5, any type of layer or coating system can be deposited (e.g., ion beam deposited or sputtered) on the smoothened surface 107 of the substrate 1. Substrate 1 may either be at room temperature or heated when a coating system is formed thereon according to different embodiments of this invention. Figs. 6-8 illustrate various DLC inclusive coating systems that may be at least partially ion beam deposited on surface 107 of substrate 1 according to different embodiments of this invention.

Figures 6(a) and 6(b) are side cross sectional views of a coated article according to an embodiment of this invention, wherein a diamond-like carbon (DLC) and fluoro-alkyl silane (FAS) inclusive coating system 5 including layers 2, 3, 4 and 6 is provided on ion beam smoothened surface 107 of substrate 1. Substrate 1 may be of glass, plastic, ceramic, or the like. However, substrate 1 is preferably glass (e.g., soda-lime-silica glass). Figure 6(a) illustrates exemplary gases (e.g., HMDSO and  $C_2H_2$  (acetylene)) which may be used in the deposition of layers 2-4, while Figure 6(b) illustrates the resulting coated article including the final resulting layers 2-4, 6 provided on substrate 1.

DLC inclusive layer 3 (e.g., having an index of refraction "n" of approximately 1.9 to 2.2, most preferably about 2.0) is provided on the substrate 1 for scratch resistance and/or durability (e.g., mechanical and/or chemical durability) purposes in order to protect the underlying substrate 1 from scratches, corrosion, and the like. Anti-reflective index matching layer 2 is located between substrate 1 and DLC inclusive layer 3 in order to

couple or approximately match the respective indices of refraction of DLC inclusive layer 3 and substrate 1. Anit-reflective layer 2 serves the purposes of enabling visible light reflectance off of the article to be reduced, thereby improving transmittance of the coated article. Layer 2 may be located directly between DLC inclusive layer 3 and substrate 1 so as to contact both of them in certain embodiments, or alternatively other layer(s) may be located between index matching layer 2 and one/both of substrate 1 and layer 3. Anti-reflective layer 2 may be referred to herein as an "index matching" layer when it has an index of refraction "n" of a value between the respective indices "n" of substrate 1 and layer 3.

Thus, the term "between" as used herein simply means that a primary layer being referred to is located at some position between two other layers regardless of whether they are in direct contact (i.e., other layer(s) may also be located between the other layers, in addition to the primary layer). For example, if a first layer is referred to herein as being located "between" second and third layers, then the first layer may or may not be in direct contact with the second and third layers (e.g., fourth and fifth layers may be located between the first and third layers). Likewise, the term "on" herein means both directly on and indirectly on. For example, if a first layer is "on" a substrate herein, the first layer may be directly on (contacting) the substrate or alternatively additional layer(s) may be located between the first layer and the substrate.

Layers 4 and 6 are optional and need not be provided in all embodiments of this invention. When provided, primer layer 4 serves to improve bonding between FAS inclusive hydrophobic layer 6 and DLC inclusive layer 3. FAS inclusive layer is provided for hydrophobic purposes, although hydrophobicity may be achieved absent FAS inclusive layer 6 in certain embodiments of this invention. As layers 4 and 6 are optional, coating system 5 may be made up of, for example, (i) layers 2, 3 only, (ii) layers 2-4 only, (iii) layers 2, 3 and 6 only, (iv) layers 2, 3, 4 and 6 only, (v) layers 2, 3, 4 and 6 with other non-illustrated layer(s) overlying the same, underlying the same, or intermingled within or between any of layers 2, 3, 4 and/or 6, (vi) layers 2 and 3 along with other non-illustrated layers, (vii) layers 2-4 along with other non-illustrated layers, (viii) layer 2 only, (ix) layer 3 only, and so on. The point here is that other layers may be provided on substrate 1 (other than those illustrated in Figs. 6(a) and 6(b)) according to different embodiments of this invention.

Starting from the substrate moving outwardly, anti-reflective layer 2 is first deposited on ion beam milled substrate 1. Layer 2 may be deposited directly on surface 107 of substrate 1 (preferable) so as to contact same, or instead other layer(s) may be located between layer 2 and substrate 1. In any event, layer 2 may be referred to herein as an "index matching" layer. This phrase "index matching" (or "index coupling") means that layer 2 has an index of refraction "n" having a value that is between the respective indices of refraction "n" values of substrate 1 and DLC inclusive layer 3, in order to

reduce visible light reflections off of the resulting coated article.

Anti-reflective layer 2 is preferably deposited on substrate 1 utilizing at least a siloxane gas, such as hexamethyldisiloxane (HMDSO) gas, via an ion beam deposition process. It is noted that oxygen (O), argon (Ar) and/or other gas(es) may also be used in combination with the siloxane (e.g., HMDSO) in forming layer 2. When HMDSO [see Fig. 14] is used during the deposition process for layer 2, either alone or in combination with other gas(es), the resulting layer 2 includes DLC and may be referred to as a DLC inclusive layer that is a hybrid amorphous mixture of DLC and  $\text{SiO}_x$  that includes  $\text{sp}^3$  carbon-carbon (C-C) bonds, silicon-oxygen (Si-O) bonds, etc. In certain other embodiments of this invention, this type of anti-reflective layer 2 may instead be formed where the HMDSO [see Fig. 14] is replaced in the ion beam deposition process with another siloxane gas or oxygen inclusive organosilicon compound gas such as but not limited to tetramethyldisiloxane (TMDSO) [see Fig. 19], octamethylcyclotetrasiloxane (OMCTSO) [see Fig. 18], tetraethoxysilane (TEOS) [see Fig. 20], any other suitable siloxane, any other suitable ethoxy substituted silane, any other alkoxy substituted silane, any other oxygen inclusive organosilicon compound inclusive gas, or any combination or mixture thereof, etc. Again, these other gas(es) may be used either alone or in combination with other gas(es) such as oxygen (O) and/or argon (Ar) to form layer 2 via an ion beam deposition or any other suitable process. Other than the O and Ar gases mentioned above, each of these gases is considered one or both of a siloxane gas or an



oxygen inclusive organosilicon compound gas, as will be appreciated by those skilled in the art.

By using the aforesaid gas(es) during the formation of anti-reflective index coupling layer 2, the resulting layer 2 even when including DLC is not as hard as DLC inclusive layer 3 because layer 2 preferably has a lesser amount/percentage of  $sp^3$  carbon-carbon (C-C) bonds than does layer 3. Moreover, the aforesaid gases enable a DLC inclusive layer 2 to be formed that has an index of refraction "n" that is from about 1.4 to 2.0, more preferably from about 1.5 to 1.8, thereby enabling layer 2 to function in an index coupling manner so as to reduce visible reflections. It is also noted that layer 2 also functions as a primer layer to improve bonding between a glass substrate 1 and DLC inclusive layer 3. Because there is more Si in layer 2 than in layer 3, layer 2 tends to bond better to substrate 1 than would layer 3 and layer 3 tends to bond better to layer 2 than it would to the substrate 1 (see discussion of TMS layer in parent application(s), incorporated herein by reference). In still further embodiments of this invention, TMS gas (see Fig. 16), 3MS gas (see Fig. 17), DMS gas (see Fig. 15), and/or any other suitable gas may be used instead of or in combination with HMDSO in the ion beam deposition of layer 2 on substrate 1.

DLC inclusive layer 3 preferably includes at least some amount of DLC in the form of highly tetrahedral amorphous carbon (ta-C) (i.e., including  $sp^3$  carbon-carbon (C-C) bonds), in order to enhance the durability and/or scratch resistance of the coated

article. In certain embodiments, one or both of layers 2 and 4 may also include at least some amount of highly tetrahedral amorphous carbon (ta-C), although typically not as much as is present in layer 3 so that layer 3 is harder than layers 2 and 4. Thus, DLC inclusive layer 3 preferably has a greater percentage per unit area of highly tetrahedral amorphous carbon (ta-C) than do either of layers 2 and 4. Highly tetrahedral amorphous carbon (ta-C) forms  $sp^3$  carbon-carbon (C-C) bonds, and is a special form of diamond-like carbon (DLC). The ta-C may be hydrogenated (i.e., ta-C:H) in certain embodiments of this invention.

DLC inclusive layer 3 may be formed and deposited on substrate 1 in any manner described for depositing a DLC inclusive layer described in any of the parent applications 09/617,815, 09/303,548, 09/442,805, or 09/583,862, all of which are incorporated herein by reference. Preferably DLC inclusive layer 3 is deposited on substrate 1 and layer 2 via an ion beam deposition process using at least a hydrocarbon gas such as  $C_2H_2$  (acetylene).

Other gas(es) such as oxygen and/or argon may be used in combination with acetylene during this deposition process. In other embodiments of this invention, acetylene gas may be replaced or complimented with e.g., any other suitable hydrocarbon gas for use in or adjacent the ion beam source during the deposition of DLC inclusive layer 3. The use of, for example, acetylene gas results in a DLC inclusive layer 3 that has more  $sp^3$  carbon-carbon (C-C) bonds than do either of layers 2 and 4. Thus, layer 3 is harder than layers 2 and 4 and functions to improve the durability (e.g., scratch resistance and/or chemical

resistance) of the resulting coated article.

Optionally, at least a surface of substrate 1 (and optionally the entire substrate 1) may be heated to from 100-400 degrees C when first DLC inclusive layer 2 is ion beam deposited thereon. Substrate 1 may or may not be maintained at this temperature when additional DLC inclusive layer(s) are deposited on the substrate following layer 2. For example, in certain embodiments, an IR heater(s) may continue to heat substrate 1 when additional DLC inclusive layers 3, 4 are deposited. Alternatively, no heat need be applied to substrate 1 when layers 2-4 are being deposited, and heat retained from a step B prior heating may be utilized to achieve results discussed herein regarding improved durability, higher density, and/or more resistance to losing hydrophobic characteristics.

In embodiments where primer layer 4 is desired, layer 4 is deposited on (either directly or indirectly) DLC inclusive layer 3 (the substrate 1 may or may not be heated as discussed above when primer layer 4 is deposited). Oxide inclusive primer layer 4 preferably is deposited on layer 3 utilizing at least a siloxane gas such as hexamethyldisiloxane (HMDSO) gas via an ion beam deposition process. It is noted that oxygen (O), argon (Ar) and/or other gas(es) may also be used in combination with the HMDSO [see Fig. 14] in forming layer 4. When HMDSO is used during the deposition process for primer layer 4, either alone or in combination with other gas(es), the resulting primer layer 4 includes DLC, and may be referred to as a DLC inclusive layer that is a hybrid amorphous mixture of DLC and  $\text{SiO}_x$  that includes  $\text{sp}^3$  carbon-carbon (C-C) bonds,

silicon-oxygen (Si-O) bonds, etc. In certain other embodiments of this invention, this type of primer layer 4 may instead be formed where the HMDSO is replaced in the deposition process with another siloxane gas or an oxygen inclusive organosilicon compound gas such as but not limited to tetramethyldisiloxane (TMDSO) [see Fig. 19],  
5 octamethylcyclotetrasiloxane (OMCTSO) [see Fig. 18], tetraethoxysilane (TEOS) [see Fig. 20], any other suitable siloxane, any other suitable ethoxy substituted silane, any other alkoxy substituted silane, any other oxygen inclusive organosilicon compound inclusive gas, any combination or mixture thereof, etc. Again, these other gas(es) may be used either alone or in combination with other gas(es) such as oxygen and/or argon to  
10 form primer layer 4 via an ion beam deposition process. Each of these gases (other than O and Ar) is considered one or both of a siloxane gas or an oxygen inclusive organosilicon compound gas, as will be appreciated by those skilled in the art.

By using these gases during the formation of primer layer 4, the resulting layer 4 even when including DLC is not as hard as DLC inclusive layer 3 because layer 4  
15 preferably has a lesser amount/percentage of  $sp^3$  carbon-carbon (C-C) bonds than does layer 3. Purposes of primer layer 4 include improving bonding between FAS inclusive layer 6 and DLC inclusive layer 3, and improving durability of the overall coating system. As for improving the bonding characteristics of FAS inclusive layer 6 to DLC inclusive layer 3, it is believed that FAS will not bond extremely well to carbon itself in layer 3, but  
20 will bond to materials such as silicon oxide which is in primer layer 4. Thus, the Si, C,

and/or O in primer layer 4 enables layer 4 to be both durable (due to the DLC in layer 4) as well as improve bonding between layers 6 and 3 (due to the C, Si and/or O in layer 4). For example, DLC inclusive layer 3 bonds well to the C and/or Si in primer layer 4, while the FAS inclusive layer 6 bonds well to the Si and/or O in primer layer 4.

5 In other embodiments of this invention, primer layer 4 need not include DLC and instead may be made of or include any of titanium oxide ( $\text{TiO}_x$ ), silicon oxide ( $\text{SiO}_x$ ),  $\text{VO}_x$ ,  $\text{HfO}_x$ , any mixture thereof, or any other suitable material such as another oxide layer. In still further embodiments of this invention, any of the aforesaid oxides may be mixed with a DLC inclusive material (e.g., deposited via HMDSO or any of the other  
10 gases discussed above) to form primer layer 4.

When a hydrophobic coating is desired, this may be achieved in any manner described in any of the parent application(s), all incorporated herein by reference. Layer 6 may or may not be needed in hydrophobic embodiments depending upon the manner in which hydrophobicity is achieved. Where fluoro-alkyl silane (FAS) compound inclusive  
15 layer 6 is desired, it may be applied on substrate 1 over layers 2, 3 and 4 as shown in Figs. 6(a) and 6(b). Due at least to hydrophobic layer 6, the resulting coating system 5 can function in a hydrophobic manner (i.e., it is characterized by high water contact angles  $\theta$  and/or low surface energies as described below), and optionally may be characterized by low tilt angle(s)  $\beta$  in certain embodiments. In general, the DLC inclusive layer(s) 2, 3  
20 and/or 4 provide durability, hydrophobicity and priming, while FAS inclusive layer 6

functions to even further increase the contact angle  $\theta$  of the coating system 5.

It is surmised that the surface of DLC inclusive primer layer 4 (or layer 3 when primer layer 4 is not present in certain embodiments) includes highly reactive dangling bonds immediately after its formation/deposition, and that the application of FAS inclusive layer 6 onto the surface of primer layer 4 shortly after layer 4's formation enables tight binding and/or anchoring of FAS inclusive layer 6 to the surface of layer 4. This results in increased contact angle  $\theta$  (improved hydrophobicity) and a durable coating system 5. In certain embodiments of this invention, it has been found that FAS inclusive layer 6 bonds more completely to DLC inclusive primer layer 4 when FAS layer 6 is applied on the upper surface of layer 4 within one hour or so after layer 4 is formed, more preferably within thirty minutes after layer 4 is formed, and most preferably within twenty minutes after layer 4 is formed. As discussed in more detail below (see Fig. 13), at least FAS inclusive layer 6 may be heated (thermally cured) after it has been deposited on the substrate 1 in order to improve its durability in certain embodiments.

Overlying layer 6 may be substantially all FAS, or only partially FAS in different embodiments of this invention. Layer 6 preferably includes at least one compound having an FAS group. Generally speaking, FAS compounds generally comprise silicon atoms bonded to four chemical groups. One or more of these groups contains fluorine and carbon atoms, and the remaining group(s) attached to the silicon atoms are typically alkyl (hydrocarbon), alkoxy (hydrocarbon attached to oxygen), or halide (e.g., chlorine)



Layers 2 and 4 may have approximately the same characteristics in certain embodiments of this invention. Alternatively, layers 2 and 4 may also have different characteristics and be deposited with different gases or gas (e.g., methane or hexane) combinations in other embodiments of this invention.

5 In an exemplary embodiment, anti-reflective index matching DLC inclusive layer 2 may be deposited using a plasma ion beam deposition technique utilizing HMDSO gas and oxygen (O) gas (e.g., the oxygen gas may flow through the ion beam source itself while the HMDSO gas may be introduced into the ion beam outside of the source itself between the slit and the substrate and/or in the source itself). Meanwhile, DLC inclusive  
10 layer 3 may be deposited using an ion beam deposition technique utilizing a C<sub>2</sub>H<sub>2</sub> (acetylene) inclusive precursor or feedstock gas either alone or in combination with oxygen and/or argon. Still further, primer DLC inclusive layer 4 may be deposited using an ion beam deposition technique utilizing HMDSO gas and both argon (Ar) and oxygen (O) gas (e.g., the oxygen/argon gases may flow through the ion beam source itself while  
15 the HMDSO gas may be introduced into the ion beam outside of the source itself between the slit and the substrate and/or in the source itself). The addition of the Ar gas for use in depositing primer layer 4 (Ar may not be used for layer 2) may cause layer 4 to have a greater hardness than layer 2, although layer 4 may still not be as hard as layer 3.



Additionally, it is believed that the underlying layer 2 (including DLC, Si and O) deposited using e.g., HMDSO functions as a barrier layer to prevent certain impurities from getting into or out of the substrate 1. Moreover, when HMDSO (see Fig. 14) is used in the deposition process of layer 2, the Si in layer 2 helps to enable overlying DLC inclusive layer 3 to better bond and/or adhere to a glass substrate 1 via layer 2.

Surprisingly, it has also been found that the use of layer 2 (e.g., deposited via HMDSO or other siloxane gas) provides a more continuous/contiguous coating on a glass surface at very thin thicknesses as compared to a DLC inclusive layer 3 deposited using  $C_2H_2$  (acetylene) gas directly on glass. As a result, layer 2 can be deposited first directly on milled glass 1 at a relatively thin thickness, and the overlying layer 3 need not be as thick as would otherwise be required. In general, the thinner the layer 3, the higher the transmission of the overall coating system. Moreover, the provision of layer 2 may enable improved yields to be achieved, as the occurrence of pinholes in the coating system is less likely.

In embodiments such as where DLC inclusive layer 3 is formed on the smoothened surface 107 of ion beam milled substrate 1 using a  $C_2H_2$  (acetylene) inclusive precursor or feedstock gas and DLC inclusive layers 2 and/or 4 is/are formed on the milled substrate using at least a HMDSO (or other siloxane or oxygen inclusive organosilicon gas) inclusive precursor or feedstock gas, then layer(s) 2 and/or 4 tend to intermix with layer 3 during the deposition process. Thus, there may not be a clear line(s) delineating or

separating layers 2, 3 and 4 in the final product due to this intermixing (i.e., ion mixing) of the material from the different layers. However, for purposes of simplicity, the layers 2-4 are referred to and illustrated herein as separate layers due to the different deposition processes (e.g., gases and/or energies) used in respective formations of adjacent layers.

5           It has been found that the DLC inclusive layer 3 formed using a hydrocarbon gas, such as  $C_2H_2$  (acetylene) inclusive precursor or feedstock, tends to have a greater hardness and density than do layers 2 and 4 formed e.g., using at least a siloxane such as HMDSO inclusive precursor or feedstock gas. For example, in certain exemplary embodiments of this invention, layer 3 may have an average hardness (measured via a nano-indentation hardness measuring technique) of from about 45-85 GPa, more  
10           preferably from about 50-70 GPa, and most preferably from about 55-60 GPa. Meanwhile, when formed via HMDSO or some other siloxane, layer(s) 2 and 4 may have an average hardness(es) of from about 1-35 GPa, and more preferably from about 10-30 GPa. Using a nano-indentation hardness measuring technique, the final coating system 5,  
15           including e.g., layers 2-4 and 6, may have an average hardness of at least about 10 GPa, more preferably from about 25-60 GPa, and even more preferably from about 30-45 GPa.

          Thus, coating system 5 includes silicon (Si) and oxygen (O) and DLC inclusive layer 2 which functions as both an index matching/coupling layer and to improve the bonding characteristics of harder DLC inclusive layer 3 to the substrate. While the Si in  
20           layer 2 improves the bonding of layer 3 to substrate 1, it is preferred that less Si be

provided in layer 3 than in layer 2 because the provision of Si in a DLC inclusive layer may result in decreased scratch resistance and/or decreased hardness. Layer 3 may or may not include Si in different embodiments of this invention. While layer 2 allows for improved bonding to the substrate and reduced visible light reflections, the provision of  
5 DLC and some  $sp^3$  carbon-carbon bonds therein allows this layer 2 to have rather high hardness values so as to render the resulting product more durable and thus resistant to scratching, abrasions, and the like. Because primer layer 4 may include DLC, Si and O in certain embodiments as well, many of these same attributes apply to layer 4 as well.

In embodiments where substrate 1 is of or includes glass (e.g., soda-lime-silica glass), anti-reflective layer 2 may be from about 10 to 250 angstroms (Å) thick, more preferably from about 10 to 150 angstroms thick, and most preferably from about 30-50 angstroms thick; DLC inclusive layer 3 may be from about 10 to 250 angstroms thick, more preferably from about 10 to 150 angstroms thick, and most preferably about 30-60 angstroms (Å) thick, and primer layer 4 may be from about 10 to 250 Å thick, more  
15 preferably from about 10 to 150 Å thick. FAS inclusive layer 6 may be from about 5-80 angstroms (Å) thick, more preferably from about 20-50 Å thick. However, these thicknesses are not limiting and the layers may be of other appropriate thicknesses in certain embodiments of this invention. Moreover, in embodiments where substrate 1 is of or includes plastic, layers 2, 3 and/or 6 may be of greater thickness(es) than those  
20 described above.

In certain embodiments, DLC inclusive layer 3 may have an approximately uniform distribution of  $sp^3$  carbon-carbon bonds throughout a large portion of its thickness, so that much of the layer has approximately the same density. In such embodiments, layers 2 and/or 4 may include a lesser percentage(s) of  $sp^3$  carbon-carbon bonds. As with layer 3, the distribution of  $sp^3$  carbon-carbon bonds in layers 2 and 4 may be approximately uniform through their respective thicknesses, or alternatively may vary. In layer 2 for example, the percentage or ratio of  $sp^3$  carbon-carbon bonds may increase throughout the thickness of the layer 2 toward layer 3. Likewise, in layer 3 the percentage or ratio of  $sp^3$  carbon-carbon bonds may be approximately uniform through the layer's thickness or instead may gradually increase throughout the thickness of the layer 3 toward layer 4. It is noted that in DLC inclusive layer 3, at least about 40% (more preferably at least about 60%, and most preferably at least about 80%) of the carbon-carbon bonds in that layer 3 are of the  $sp^3$  carbon-carbon type. In each of layers 2 and 4, at least about 5% (more preferably at least about 10%, and most preferably at least about 20%) of the carbon-carbon bonds are of the  $sp^3$  carbon-carbon type. However, in layers 2 and 4 a lesser percentage of the total bonds in the entire layer(s) are  $sp^3$  carbon-carbon type bonds due to the presence of, e.g., Si and O in these layers.

It is believed that the presence of  $sp^3$  carbon-carbon bonds in layers 2-4 increases the density and hardness of the coating system, thereby enabling it to satisfactorily function in automotive environments. Moreover, it is believed that heating substrate 1 as

described above and/or shown in Fig. 21, so that the substrate 1 is heated/hot when DLC inclusive layer(s) 2, 3 and/or 4 are deposited thereon, results in one or more of layers 2-4 having increased density. Layers 2-4 may or may not include  $sp^2$  carbon-carbon bonds in different embodiments, although formation of  $sp^2$  carbon-carbon bonds is likely in all of these layers and even preferred to some extent especially in layers 2 and 4.

When hydrophobicity is desired, in order to improve the hydrophobic nature of coating system 5 atoms in addition to carbon (C) may be provided in at least layer 3 when layers 4 and 6 are not provided. For example, in certain embodiments of this invention when layer 3 is the outermost layer, that layer 3 (taking the entire layer thickness, or only a thin 10 Å thick layer portion thereof into consideration) may include in addition to the carbon atoms of the  $sp^3$  carbon-carbon bonds, by atomic percentage, from about 0-20% Si (more preferably from about 0-10%), from about 0-20% oxygen (O) (more preferably from about 0-15%), and from about 5-60% hydrogen (H) (more preferably from about 5-35% H). Optionally, in such embodiments layer 3 may include from about 0-10% (atomic percentage) fluorine (F) (more preferably from about 0-5% F) in order to further enhance hydrophobic characteristics of the coating. This is discussed in more detail in one or more of the parent cases, incorporated herein by reference. In general, the provision of H in layer 3 reduces the number of polar bonds at the coating's surface, thereby improving the coating system's hydrophobic properties. These material(s) may or may not be provided in layer 3 when a hydrophobic coating system is not desired, or when layers 4

and 6 are provided in the system.

Figure 6(c) is a side cross sectional view of a coated article according to another embodiment of this invention, the coated article including ion beam milled substrate 1 and layers 2 and 3 thereon. This Fig. 6(c) embodiment is similar to the Fig. 6(a)-6(b) embodiment, except that layers 4 and 6 are not provided in this embodiment. Thus, for example, the coated article may include milled substrate 1 (e.g., glass) on which layer 2 (e.g., formed using a HMDSO, or other siloxane or oxygen inclusive organosilicon gas) and DLC inclusive layer 3 (e.g., formed using  $C_2H_2$  gas) are formed. This coated article may or may not be hydrophobic in different embodiments of this invention, although hydrophobic is preferred.

Figure 6(d) illustrates a coated article according to another embodiment of this invention. This Fig. 6(d) embodiment is similar to the Fig. 6(a)-6(b) embodiment, except that layers 2, 4 and 6 are not provided in this embodiment. Thus, for example, the coated article may include ion beam milled substrate 1 (e.g., glass) on which DLC inclusive layer 3 (e.g., formed using  $C_2H_2$  gas) is formed. Any additional layers are merely optional. Layer 3 may be doped with H or the like in versions of this embodiment to increase contact angle  $\theta$ . Thus, as will all other embodiments herein, coated articles according to this embodiment may have an initial contact angle  $\theta$  of at least about 55 degrees (more preferably of at least about 80 degrees, even more preferably of at least about 100 degrees, and most preferably of at least about 110 degrees).

Figure 6(e) illustrates a coated article according to another embodiment of this invention. This Fig. 6(e) embodiment is the same as the Fig. 6(d) embodiment described above, except that FAS inclusive layer 6 is also provided on the ion beam milled substrate 1 over DLC inclusive layer 3.

5 Figure 7 is a side cross sectional view of a coated article according to another embodiment of this invention, including ion beam milled substrate 1 (e.g. glass), DLC inclusive coating system 5 including layers 2, 3, 4 and 6 as described above with regard to the Fig. 6 embodiment, and intermediate layer(s) 7 provided between layer 2 and substrate 1. Intermediate layer 7 may be of or include, for example, any of silicon nitride, silicon oxide, an infrared (IR) reflecting layer or layer system, an ultraviolet (UV) reflecting layer or layer system, another DLC inclusive layer(s), or any other type of desired layer(s). In this embodiment, it is noted that coating system 5 is still "on" substrate 1. The term "on" herein means that substrate 1 supports DLC coating system 5, regardless of whether or not other layer(s) (e.g. 7) are provided therebetween (this also applies to the term "over" herein). Thus, coating system 5 may be provided directly on milled substrate 1 as shown in Fig. 1, or may be provided on milled substrate 1 with another coating system or layer 7 therebetween as shown in Fig. 7. Exemplar coatings/layers that may be used as low-E or other coating(s)/layer(s) 7 are shown and/or described in any of U.S. Patent Nos. 5,837,108, 5,800,933, 5,770,321, 5,557,462, 5,514,476, 5,425,861, 5,344,718, 5,376,455, 5,298,048, 5,242,560, 5,229,194, 5,188,887 and 4,960,645, which are all hereby

incorporated herein by reference.

Figure 8 illustrates another embodiment of this invention that is the same as the Figure 6 embodiment, except that primer layer 4 is not provided. It has been found that primer layer 4 need not be provided in all embodiments of this invention. Likewise, in other embodiments of this invention (not shown), FAS inclusive layer 6 need not be provided. In still further embodiments (not shown), one or more intermediate layer(s) 7 may be provided between layer 2 and ion beam milled substrate 1 in the Figure 8 embodiment.

Referring to the different embodiments of Figs. 6-8, coating system 5 is at least about 60% transparent to or transmissive of visible light rays, more preferably at least about 70 % transmissive, even more preferably at least about 85% transmissive, and most preferably at least about 95% transmissive of visible light rays.

When substrate 1 is of glass, it may be from about 1.0 to 5.0 mm thick, preferably from about 2.3 to 4.8 mm thick, and most preferably from about 3.7 to 4.8 mm thick. In certain embodiments, another advantage of coating system 5 is that the ta-C (e.g., in layers 2-4) therein may reduce the amount of soda (e.g., from a soda-lime-silica glass substrate 1) that can reach the surface of the coated article and cause stains/corrosion. In such embodiments, substrate 1 may be soda-lime-silica glass and include, on a weight basis, from about 60-80% SiO<sub>2</sub>, from about 10-20% Na<sub>2</sub>O, from about 0-16% CaO, from about 0-10% K<sub>2</sub>O, from about 0-10% MgO, and from about 0-5% Al<sub>2</sub>O<sub>3</sub>. Iron and/or



other additives may also be provided in the glass composition of the substrate 1. In certain other embodiments, substrate 1 may be soda lime silica glass including, on a weight basis, from about 66-75% SiO<sub>2</sub>, from about 10-20% Na<sub>2</sub>O, from about 5-15% CaO, from about 0-5% MgO, from about 0-5% Al<sub>2</sub>O<sub>3</sub>, and from about 0-5% K<sub>2</sub>O. Most preferably, substrate 1 is soda lime silica glass including, by weight, from about 70-74% SiO<sub>2</sub>, from about 12-16% Na<sub>2</sub>O, from about 7-12% CaO, from about 3.5 to 4.5% MgO, from about 0 to 2.0% Al<sub>2</sub>O<sub>3</sub>, from about 0-5% K<sub>2</sub>O, and from about 0.08 to 0.15% iron oxide. Soda lime silica glass according to any of the above embodiments may have a density of from about 150 to 160 pounds per cubic foot (preferably about 156), an average short term bending strength of from about 6,500 to 7,500 psi (preferably about 7,000 psi), a specific heat (0-100 degrees C) of about 0.20 Btu/lbF, a softening point of from about 1330 to 1345 degrees F, a thermal conductivity of from about 0.52 to 0.57 Btu/hrftF, and a coefficient of linear expansion (room temperature to 350 degrees C) of from about 4.7 to 5.0 x 10<sup>-6</sup> degrees F. Also, soda lime silica float glass available from Guardian Industries Corp., Auburn Hills, Michigan, may be used as substrate 1, and then milled as discussed above regarding Figs. 1-5. Any such aforesaid glass substrate 1 may be, for example, green, blue or grey in color when appropriate colorant(s) are provided in the glass in certain embodiments.

In certain other embodiments of this invention, substrate 1 may be of borosilicate glass, or of substantially transparent plastic, or alternatively of ceramic. In certain

borosilicate embodiments, the substrate 1 may include from about 75-85%  $\text{SiO}_2$ , from about 0-5%  $\text{Na}_2\text{O}$ , from about 0 to 4%  $\text{Al}_2\text{O}_3$ , from about 0-5%  $\text{K}_2\text{O}$ , from about 8-15%  $\text{B}_2\text{O}_3$ , and from about 0-5%  $\text{Li}_2\text{O}$ .

In still further embodiments, an automotive window (e.g. windshield or side window) including any of the above glass substrates laminated to a plastic substrate may combine to make up substrate 1, with the coating system(s) of any of the Figs. 6-8 embodiments or any other embodiment herein provided on the outside or inside milled surface(s) of such a window. In other embodiments, substrate 1 may include first and second glass sheets of any of the above mentioned glass materials laminated to one another, for use in window (e.g. automotive windshield, residential window, commercial architectural window, automotive side window, vacuum IG window, automotive backlight or back window, etc.) and other similar environments.

In hydrophobic embodiments of this invention, hydrophobic performance of the coating system of any of the Figs. 6-8 embodiments is a function of contact angle  $\theta$ , surface energy  $\gamma$ , tilt angle  $\beta$ , and/or wettability or adhesion energy  $W$ .

The surface energy  $\gamma$  of a coating system may be calculated by measuring its contact angle  $\theta$  (contact angle  $\theta$  is illustrated in Figs. 9(a) and 9(b)). Fig. 9(a) shows the contact angle of a drop on a substrate absent this invention, while Fig. 9(b) shows the contact angle of a drop on a substrate having a coating system thereon according to a hydrophobic embodiment of this invention. A sessile drop 31 of a liquid such as water is

placed on the coating as shown in Fig. 9(b). A contact angle  $\theta$  between the drop 31 and underlying coating system 5 appears, defining an angle depending upon the interface tension between the three phases in the point of contact. Generally, the surface energy  $\gamma_C$  of a coating system can be determined by the addition of a polar and a dispersive component, as follows:  $\gamma_C = \gamma_{CP} + \gamma_{CD}$ , where  $\gamma_{CP}$  is the coating's polar component and  $\gamma_{CD}$  the coating's dispersive component. The polar component of the surface energy represents the interactions of the surface which is mainly based on dipoles, while the dispersive component represents, for example, van der Waals forces, based upon electronic interactions. Generally speaking, the lower the surface energy  $\gamma_C$  of coating system 5, the more hydrophobic the coating and the higher the contact angle  $\theta$ .

Adhesion energy (or wettability)  $W$  can be understood as an interaction between polar with polar, and dispersive with dispersive forces, between the coating system and a liquid thereon such as water.  $\gamma^P$  is the product of the polar aspects of liquid tension and coating/substrate tension; while  $\gamma^D$  is the product of the dispersive forces of liquid tension and coating/substrate tension. In other words,  $\gamma^P = \gamma_{LP} * \gamma_{CP}$ ; and  $\gamma^D = \gamma_{LD} * \gamma_{CD}$ ; where  $\gamma_{LP}$  is the polar aspect of the liquid (e.g. water),  $\gamma_{CP}$  is the polar aspect of coating system (e.g., coating system 5);  $\gamma_{LD}$  is the dispersive aspect of liquid (e.g. water), and  $\gamma_{CD}$  is the dispersive aspect of the coating system. It is noted that adhesion energy (or effective interactive energy)  $W$ , using the extended Fowkes equation, may be determined by:

$$W = [\gamma_{LP} * \gamma_{CP}]^{1/2} + [\gamma_{LD} * \gamma_{CD}]^{1/2} = \gamma_l (1 + \cos\theta), \text{ where } \gamma_l \text{ is liquid tension and } \theta \text{ is}$$

the contact angle.  $W$  of two materials is a measure of wettability indicative of how hydrophobic the coating system is.

When analyzing the degree of hydrophobicity of outermost layer/portion of the coating system 5 with regard to water, it is noted that for water  $\gamma_{LP}$  is 51 mN/m and  $\gamma_{LD}$  is 22 mN/m. In certain embodiments of this invention, the polar aspect  $\gamma_{CP}$  of surface energy of layers 3, 4 and/or 6 is from about 0 to 0.2 (more preferably variable or tunable between 0 and 0.1) and the dispersive aspect  $\gamma_{CD}$  of the surface energy of layers 3, 4 and/or 6 is from about 16-22 mN/m (more preferably from about 16-20 mN/m). Using the above-listed numbers, according to certain embodiments of this invention, the surface energy  $\gamma_C$  of layer 6 (or 3 in certain embodiments) (and thus coating system 5) is less than or equal to about 20.2 mN/m, more preferably less than or equal to about 19.5 mN/m, and most preferably less than or equal to about 18.0 mN/m; and the adhesion energy  $W$  between water and the coating system is less than about 25 mN/m, more preferably less than about 23 mN/m, even more preferably less than about 20 mN/m, and most preferably less than about 19 mN/m. These low values of adhesion energy  $W$  and the coating system's surface energy  $\gamma_C$ , and the high initial contact angles  $\theta$  achievable, illustrate the improved hydrophobic nature of the coating systems 5 according to different embodiments of this invention. While layers 3, 4 and/or 6 functions to provide much of the hydrophobic nature of the coating system 5, optional underlying DLC inclusive layer 2 improves the bonding characteristics of the coating system 5 to the substrate 1 (e.g.,

glass substrate) and yet still provides adequate hardness characteristics regarding the coating system 5 as a whole.

The initial contact angle  $\theta$  of a conventional glass substrate 1 with sessile water drop 31 thereon is typically from about 22-24 degrees, although it may dip as low as 17 or so degrees in some circumstances, as illustrated in Figure 9(a). Thus, conventional glass substrates are not particularly hydrophobic in nature. In hydrophobic embodiments of this invention, the provision of coating system 5 on substrate 1 causes the contact angle  $\theta$  to increase to the angles discussed herein. as shown in Fig. 9(b) for example, thereby improving the hydrophobic nature of the article. As discussed in Table 1 of 09/303,548, the contact angle  $\theta$  of a ta-C DLC layer is typically less than 50 degrees, although it may be higher than that in certain circumstances as a function of ion energy. However, the makeup of DLC-inclusive coating system 5 described herein (with or without FAS inclusive layer 6) enables the initial contact angle  $\theta$  of the system relative to a water drop (i.e. sessile drop 31 of water) to be increased in certain embodiments to at least about 55 degrees, more preferably of at least about 80 degrees, even more preferably to at least about 100 degrees, even more preferably at least about 110 degrees, and most preferably at least about 125 degrees, thereby improving the hydrophobic characteristics of the DLC-inclusive coating system. An "initial" contact angle  $\theta$  means prior to exposure to environmental conditions such as sun, rain, abrasions, humidity, etc. As discussed above, heating of substrate 1 before and/or during ion beam deposition of DLC inclusive layer(s)

thereon can increase the resulting coated article's resistance to diminishing contact angle upon exposure to UV radiation and/or friction such as wiper blades.

Figures 10-11 illustrate an exemplary linear or direct ion beam source 25 which may be used to ion beam mill substrate 1 as shown and discussed with regard to Figs. 1-5, to deposit layers 2, 3 and 4 of coating system 5, clean a substrate, or surface plasma treat a DLC inclusive coating with H and/or F according to different embodiments of this invention. Ion beam source 25 includes gas/power inlet 26, anode 27, grounded cathode magnet portion 28, magnet poles 29, and insulators 30. A 3kV DC power supply may be used for source 25 in some embodiments. Linear source ion deposition allows for substantially uniform deposition of layers 2-4 as to thickness and stoichiometry. The ion beam from the source may be focused or non-focused in different embodiments of this invention. As mentioned above, FAS inclusive layer 6 is preferably not applied using ion beam technology (rubbing/buffing is a preferred deposition technique for layer 6), although it may be formed in such a manner in certain embodiments of this invention.

Ion beam source 25 is based upon a known gridless ion source design. The linear source is composed of a linear shell (which is the cathode and grounded) inside of which lies a concentric anode (which is at a positive potential). This geometry of cathode-anode and magnetic field 33 gives rise to a close drift condition. The anode layer ion source can also work in a reactive mode (e.g. with oxygen and nitrogen). The source includes a metal housing with a slit in a shape of a race track as shown in Figures 10-11. The

hollow housing is at ground potential. The anode electrode is situated within the cathode body (though electrically insulated) and is positioned just below the slit. The anode can be connected to a positive potential as high as 3,000 or more volts (V). Both electrodes may be water cooled in certain embodiments. Feedstock/precursor gases (e.g. Ar, acetylene, etc.), described herein, are fed through the cavity between the anode and cathode. The gas(es) used determines the make-up of the resulting layer deposited on an adjacent substrate 1, or the type of milling beam impinging upon the substrate.

The linear ion source also contains a labyrinth system that distributes the precursor gas (e.g., TMS (i.e.,  $(\text{CH}_3)_4\text{Si}$  or tetramethylsilane); acetylene (i.e.,  $\text{C}_2\text{H}_2$ ); 3MS (i.e., trimethyldisilane); DMS (i.e., dichloro-dimethylsilane); hexane; methane; Ar; Kr; Xe; Ne; HMDSO (i.e., hexamethyldisiloxane); TEOS (i.e., tetraethoxysilane), etc.) fairly evenly along its length and which allows it to supersonically expand between the anode-cathode space internally. The electrical energy then cracks the gas to produce a plasma within the source. The ions (e.g.,  $\text{Ar}^+$  ions) are expelled out at energies in the order of  $eV_{c-a}/2$  when the voltage is  $V_{c-a}$ . The ion beam emanating from the slit is approximately uniform in the longitudinal direction and has a Gaussian profile in the transverse direction. Exemplary ions 34 are shown in Figure 11. A source as long as one meter may be made, although sources of different lengths are anticipated in different embodiments of this invention. Finally, electron layer 35 is shown in Figure 11 completes the circuit thereby enabling the ion beam source to function properly.

In certain embodiments of this invention, gases discussed herein (e.g., HMDSO, TEOS, acetylene, hexane, argon, methane, etc.) may be fed through the ion beam source via cavity 42 until they reach the area near slit 44 where they are ionized. However, in other embodiments of this invention described above, a gas such as HMDSO (e.g., for layers 2 and 4) may be injected into the ion beam at location 39 between the slit and the substrate 1, while gas such as oxygen and/or argon is caused to flow through cavity 42 in the source itself adjacent the ion emitting slit 44. Alternatively, gases such as HMDSO, TEOS, etc. may be injected into the ion beam both at 39 and via cavity 42.

In alternative embodiments of this invention, an ion beam source device or apparatus as described and shown in Figs. 1-3 of U.S. Patent No. 6,002,208 (hereby incorporated herein by reference in its entirety) may be used to deposit/form DLC inclusive layers 2-4 on milled substrate 1 in accordance with any of the Fig. 6-8 embodiments of this invention. One or multiple such ion beam source devices may be used (e.g., one source may deposit all layers 2-4, or alternatively a different source may be used for each of layers 2-4). In certain embodiments, another ion beam source may be provided for initially cleaning the surface of substrate 1 prior to deposition of layers 2-4. After layers 2-4 are deposited, FAS inclusive layer 6 is preferably applied or deposited thereon.

Referring to Fig. 12, tilt angle  $\beta$  characteristics associated with certain embodiments of this invention will be explained. In a hydrophobic coating, it is often



desirable in certain embodiments to have a high contact angle  $\theta$  (see Fig. 9(b)) in combination with a low tilt angle  $\beta$ . As shown in Fig. 12, tilt angle  $\beta$  is the angle relative to the horizontal 43 that the coated article must be tilted before a 30  $\mu$ L (volume) drop 41 (e.g., of water) thereon begins to flow down the slant at room temperature without significant trail. A low tilt angle means that water and/or other liquids may be easily removed from the coated article upon tilting the same or even in high wind conditions. In certain embodiments of this invention, coated articles herein have an initial tilt angle  $\beta$  of no greater than about 30 degrees, more preferably no greater than about 20 degrees, and even more preferably no greater than about 10 degrees. In certain embodiments, the tilt angle does not significantly increase over time upon exposure to the environment and the like, while in other embodiments it may increase to some degree over time.

Figure 21 illustrates steps taken in the manufacture of a coated article according to an exemplary embodiment of this invention where the ion beam milled substrate is heated before and/or when the coating system is deposited thereon. First, an ion beam milled glass substrate (e.g., soda-lime-silica glass) 1 is provided upon which a coating system is to be deposited (step A). The glass substrate 1 is then heated (e.g., by an IR heater(s)) just prior to a DLC inclusive layer being deposited on the substrate (step B). Preferably, substrate 1 is heated to a temperature of from about 100 to 400 degrees C (more preferably from about 200-350 degrees C) by an infrared (IR) heater just prior to application of the DLC inclusive layer(s). A single IR heater may be located so as to





lowered so as to reduce visible light reflections off of the final coated article.

After layer 2 has been formed, either the same or another ion beam source is used to deposit layer 3 over (directly on in preferred embodiments) layer 2. Heating may or may not continue of the substrate 1 during deposition of layer 3 thereon. To deposit overlying DLC inclusive layer 3, another gas such as at least  $C_2H_2$  is fed through the source (or inserted at location 39) so that the source expels the ions necessary to form layer 3 overlying layer 2 on substrate 1. The  $C_2H_2$  gas may be used alone, or in exemplary alternative embodiments the gas may be produced by bubbling a carrier gas (e.g.  $C_2H_2$ ) through a precursor monomer (e.g. TMS or 3MS) held at about 70 degrees C (well below the flashing point). Acetylene feedstock gas ( $C_2H_2$ ) is used in certain embodiments for depositing layer 3 to prevent or minimize/reduce polymerization (layer 2 may or may not be polymerized in certain embodiments) and to obtain an appropriate energy to allow the ions to penetrate the surface on the substrate/layer 2 and subimplant therein, thereby causing layer 3 to intermix with layer 2 in at least an interface portion between the layers. The actual gas flow may be controlled by a mass flow controller (MFC) which may be heated to about 70 degrees C. In certain optional embodiments, oxygen ( $O_2$ ) gas may be independently flowed through an MFC. The temperature of milled substrate 1 may be as discussed above; an arc power of about 1000 W may be used; precursor gas flow may be about 25 sccm; the base pressure may be about  $10^{-6}$  Torr. The optimal ion energy window for the majority of layers 2, 3 is from about 100-1,000

eV (preferably from about 100-400 eV) per carbon ion. At these energies, the carbon in the resulting layers 2, 3 emulates diamond, and  $sp^3$  C-C bonds form. However, compressive stresses can develop in ta-C when being deposited at 100-150 eV. Such stress can reach as high as 10 GPa and can potentially cause delamination from many substrates. It has been found that these stresses can be controlled and decreased by using an ion energy during the deposition process in a range of from about 200-1,000 eV. As stated above, layers 2 and 3 intermix with one another at the interface between the two layers, thereby improving the bonding between the layers. At particle energies (carbon energies) of several hundred eV, a considerable material transport can take place over several atomic distances. This is caused by the penetration of fast ions and neutrals as well as by the recoil displacement of struck atoms. At sufficiently high particle energies and impact rates, there is an enhanced diffusion of the thermally agitated atoms near the film surface that occurs via the continuously produced vacancies. In the formation of ta-C:H, these effects can help improve film adhesion by broadening the interface (i.e., making it thicker, or making an interfacial layer between the two layers 2 and 3 (or between layer 2 and glass 1) due to atom mixing). After layer 2 is deposited, the carbon from layer 3 implants into layer 2 (i.e., subimplantation) so as to make the bond better of layer 3 to the substrate. Thus, layers 2 and 3 are contiguous due to this intermixing, and this "smearing" between the layers enhances the adhesion of layer 3 to both layer 2 and thus the substrate 1.

High stress is undesirable in the thin interfacing portion of layer 2 that directly contacts the surface of a glass substrate 1 in the Figure 6 embodiment. Thus, for example, the first 1-40% thickness (preferably the first 1-20% and most preferably the first 5-10% thickness) of layer 2 may optionally be deposited on substrate 1 using high anti-stress energy levels of from about 200-1,000 eV, preferably from about 400-500 eV. Then, after this initial interfacing layer portion of layer 2 has been grown, the ion energy in the ion deposition process may be decreased (either quickly or gradually while deposition continues) to about 100-200 eV, preferably from about 100-150 eV, to grow the remainder of layer(s) 2 and/or layer(s) 3-4. Thus, in certain embodiments, because of the adjustment in ion energy and/or gases during the deposition process, DLC inclusive layers 2-4 may optionally have different densities and different percentages of  $sp^3$  C-C bonds at different layer portions thereof (the lower the ion energy, the more  $sp^3$  C-C bonds and the higher the density).

While direct ion beam deposition techniques are preferred in certain embodiments, other methods of deposition may also be used in different embodiments. For example, filtered cathodic vacuum arc ion beam techniques may be used to deposit layers 2-4. Also, in certain embodiments,  $CH_4$  may be used as a feedstock gas during the deposition process instead of or in combination with the aforesaid  $C_2H_2$  gas.

After layers 2-3 have been deposited, primer layer 4 is deposited in a manner similar to that described above for layer 2. However, in one particular example, the gases

used in forming layer 4 may include in addition to the HMDSO and oxygen described above, argon (Ar) mixed with the oxygen gas in order to enable more  $sp^3$  C-C bonds to be formed in layer 4 than in layer 2 so that layer 4 is harder than layer 2 (for durability purposes). The Ar/O mixture is preferably fed through the source via cavity 42 while the HMDSO gas is preferably inserted into the ion beam at 39, or alternatively may in addition or instead be caused to flow through the source at 42 along with the Ar/O gas mixture.

After DLC inclusive layers 2-4 have been formed on substrate 1, FAS inclusive layer 6 is deposited thereon or applied thereto as shown in Fig. 6 (e.g., by rubbing or otherwise applying/depositing this layer 6 in any other suitable manner).

After FAS inclusive layer 6 has been formed on the substrate 1, the coated article may be again heated (e.g., at about 70-200 degrees C this time). Surprisingly, as mentioned previously, it has been found that heating the coated article in such a manner after deposition of layer 6 improves the durability of FAS inclusive layer 6, and thus of the overall coating system. It is thought that such heating may "cure" layer 6 or otherwise cause it to more completely bond to itself and/or layer 4.

Figure 13 is a flowchart illustrating that according to certain optional embodiments of this invention, FAS inclusive layers may be thermally cured after being deposited. A substrate 1 (e.g., glass, plastic, or ceramic substrate) is provided at step 10, and then milled (see Figs. 1-5). At least one DLC inclusive layer 2-4 is deposited on the ion beam





properties discussed above.

As will be appreciated by those skilled in the art, coated articles according to different embodiments of this invention may be utilized in the context of automotive windshields, automotive side windows, automotive backlites (i.e., rear windows), architectural windows, residential windows, ceramic tiles, shower doors, and the like.

Once given the above disclosure, many other features, modifications, and improvements will become apparent to the skilled artisan. Such other features, modifications, and improvements are, therefore, considered to be a part of this invention, the scope of which is to be determined by the following claims. For example and without limitation, certain coated articles according to this invention may be hydrophobic, other coated articles according to this invention may be hydrophilic, and still other coated articles according to this invention may be neither hydrophobic nor hydrophilic.